Muon Collider summary from the Accelerator Frontier

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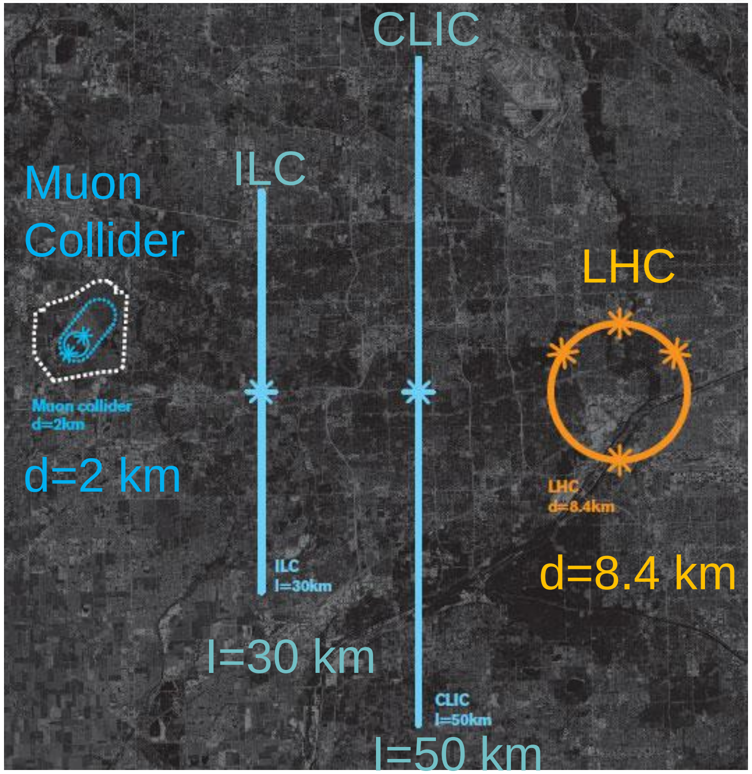
Muon Collider forum kickoff meeting

January 27, 2021

Outline

- Muon Collider overview
- Challenges
- Accelerator subsystems
- Summary of past accomplishments
- Comments and future work

Muon Collider (I)

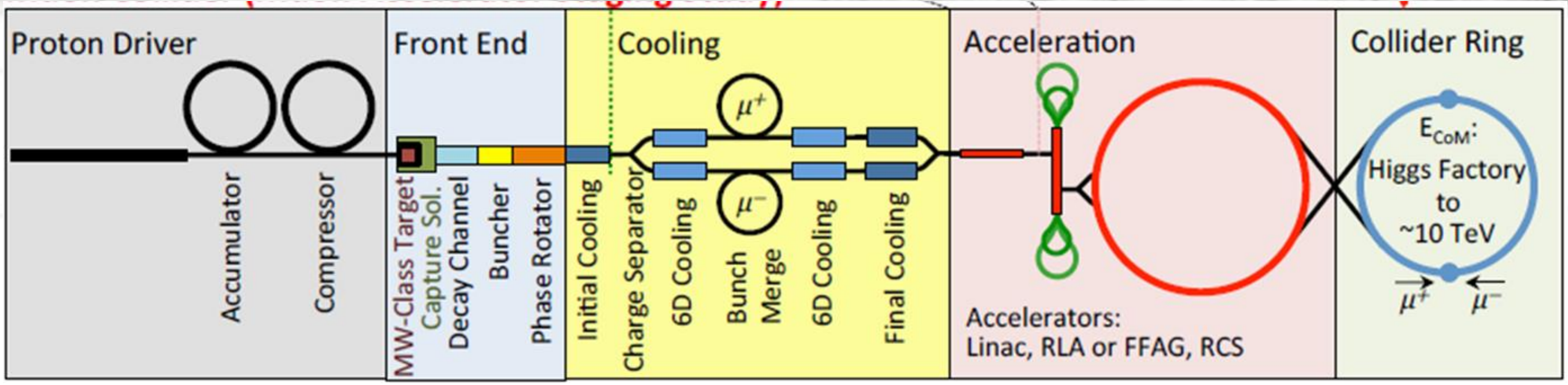


- A Muon Collider (MC) would offer a precision probe of fundamental interactions but in much smaller foot print as compared to electron or proton machines.

MC accelerator challenges

- Assuming a proton driven collider, there are some challenges:
- Muon beams are born as tertiary beams
  - Protons -> Pions -> Muons
  - Requires a sophisticated manipulation scheme for muon production, capture and transport
  - Must deal with other contaminants (protons, electrons)
- Muons are born with a large phase-space
  - Requires significant tailoring of the 6D phase-space distribution
- Unlike electrons, muons decay
  - Everything must be done fast

Muon accelerator overview



- Between 2011-2016 MAP collaboration was formed to address key feasibility issues of a Muon Collider
  - Leveraged prior decades of study to identify a design path. Focused on proton-driver based solution
- Due to an increase in MC physics interest, discussions towards a formal International Muon Collaboration begun in 2020, mainly driven by European institutes
  - Considers a proton driven solution (like MAP)

MC accelerator components

- High power (MW scale) proton driver
  - Considered 8 GeV H- SRF linac at 2-4 MW
- Pre-target accumulation & compression rings for 2 ns bunches
- Target & capture solenoid to create 200 MeV secondaries
  - Considered liquid Mercury targets at 20 T fields
- Ionization cooling channel to reduce the 6D phase-space by several orders of magnitude
  - Considered km scale channels with ~30 T magnets at the end
- Acceleration system to bring the beam at TeV scale energies
  - For multi-TeV scale, considered rapid cycling synchrotrons using SRF
- A collider ring where counter propagating muons collide

Muon Collider parameters (I)

- Parameters as developed by the MAP effort

Parameter	Units	Higgs	Top-high resolution	Top-high luminosity	Multi-TeV		
CoM energy	TeV	0.126	0.35	0.35	1.5	3.0	6.0*
Avg. luminosity	10^{34} cm$^{-2}s^{-1}$	0.008	0.07	0.6	1.25	4.4	12
Beam energy spread	%	0.004	0.01	0.1	0.1	0.1	0.1
Higgs production/10^7 sec		13,500	7000	60,000	37,500	200,000	820,000
Circumference	km	0.3	0.7	0.7	2.5	4.5	6
Ring depth [1]	m	135	135	135	135	135	540
No. of IPs		1	1	1	2	2	2
Repetition rate	Hz	15	15	15	15	12	6
$\beta^*_{x,y}$	cm	1.7	1.5	0.5	1 (0.5–2)	0.5 (0.3–3)	0.25
No. muons/bunch	10^{12}	4	4	3	2	2	2
Norm. trans. emittance, ε_T	π mm-rad	0.2	0.2	0.05	0.025	0.025	0.025
Norm. long. emittance, ε_L	π mm-rad	1.5	1.5	10	70	70	70
Bunch length, σ_s	cm	6.3	0.9	0.5	1	0.5	0.2
Proton driver power	MW	4	4	4	4	4	1.6
Wall plug power	MW	200	203	203	216	230	270

* Accounts for off-site neutrino radiation

Muon Collider parameters (II)

- Under consideration by the International MC collaboration - 2020

Target integrated luminosities

$\sqrt{s}$	$\int \mathcal{L}dt$
3 TeV	1 ab^{-1}
10 TeV	10 ab^{-1}
14 TeV	20 ab^{-1}

Reasonably conservative

- each point in 5 years with tentative target parameters
- FCC-hh to operate for 25 years
- Aim to have two detectors
- But might need some operational margins

Note: focus on 3 and 10 TeV
Have to define staging strategy

Tentative target parameters, scaled from MAP parameters

Parameter	Unit	3 TeV	10 TeV	14 TeV
L	10^{34} cm^{-2}s^{-1}	1.8	20	40
N	10^{12}	2.2	1.8	1.8
f_r	Hz	5	5	5
P_{beam}	MW	5.3	14.4	20
C	km	4.5	10	14
<B>	T	7	10.5	10.5
ε_L	MeV m	7.5	7.5	7.5
σ_E / E	%	0.1	0.1	0.1
σ_z	mm	5	1.5	1.07
β	mm	5	1.5	1.07
ε	µm	25	25	25
$\sigma_{x,y}$	µm	3.0	0.9	0.63

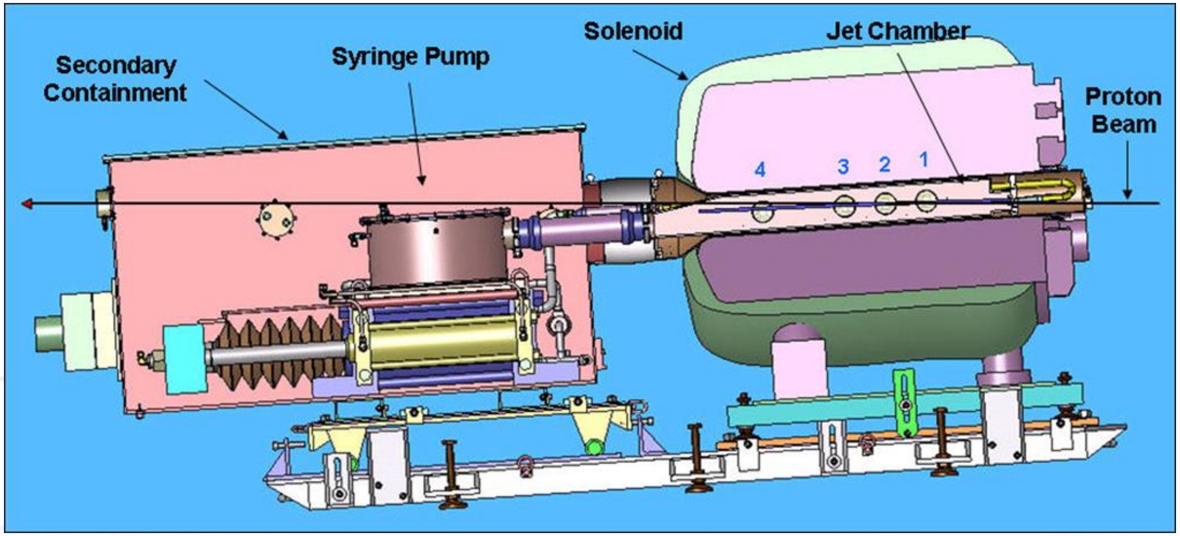
Snowmass process to give feedback on this

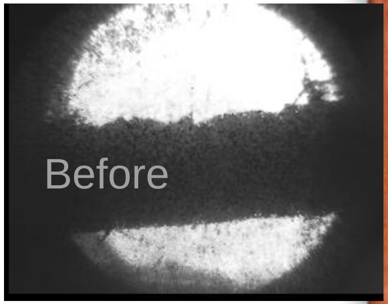
Progress review: Design, hardware R&D and experimental programs

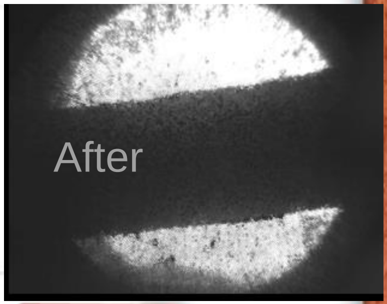
- Targetry R&D and proof-of-principle demonstration at CERN
- Demonstration of operation of normal conducting (NCD) RF cavities in the presence of strong magnetic fields
- Demonstration of transverse ionization cooling by the International Muon Ionization Cooling Experiment (MICE) hosted by RAL
- Muon emittance exchange demonstrated at the Fermilab Muon Campus and MICE
- Superconducting magnet development suitable for Muon Colliders
- End-to-end muon ionization cooling channel models that meet the MC requirements

Target technology

- MERIT experiment at CERN PS (2007):
  - Proof-of-principle demonstration of a liquid mercury jet target in a high-field solenoid field
  - Demonstrated that the technology is OK for beam powers up to 8 MW with a repetition rate of 70 Hz.

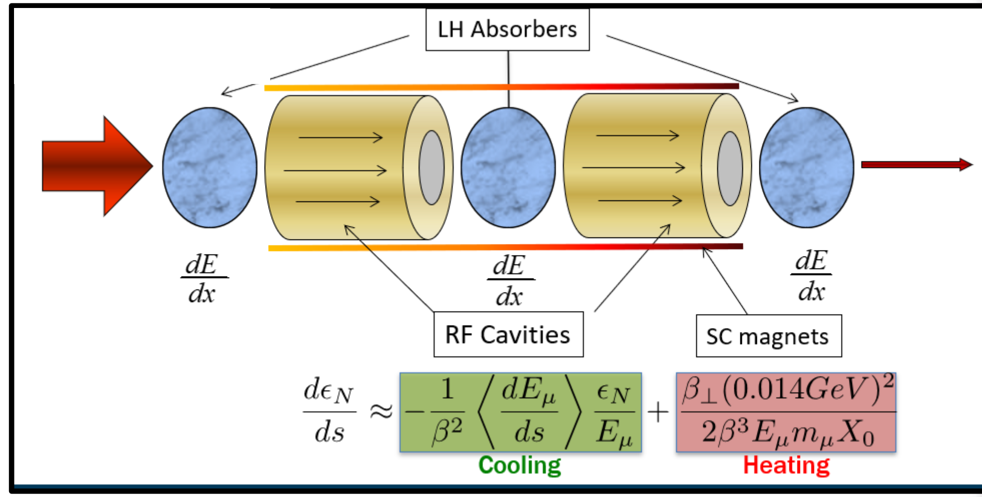


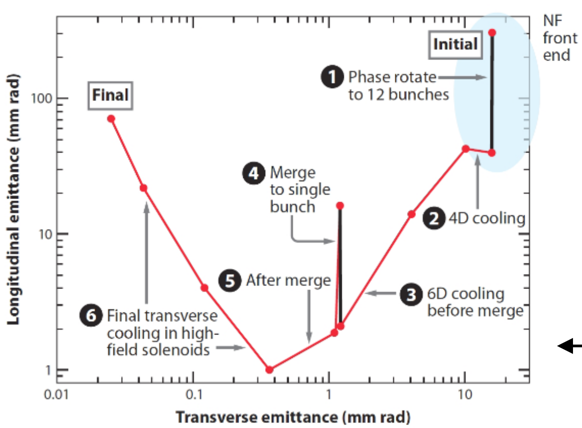




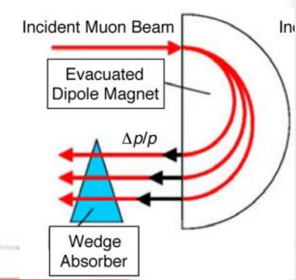
Muon cooling

- The desired 6D emittance for a MC is 5-6 orders of magnitude less from the emittance of the beam at the target
- Muon ionization cooling can do this before muons decay:
  - Requires rf cavities to compensate for lost longitudinal energy
  - Use strong B-fields to confine beams

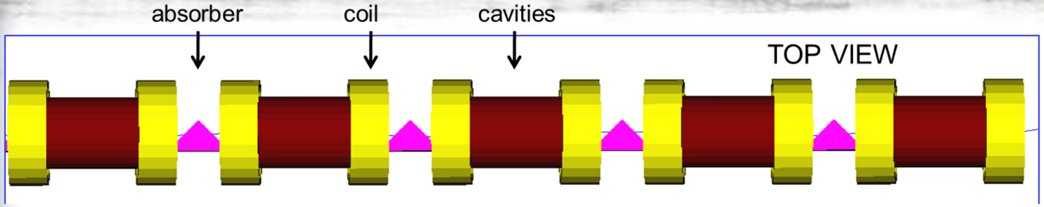




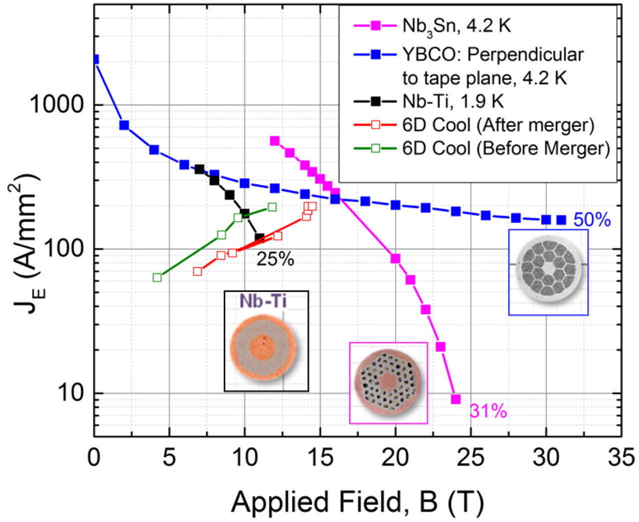
← Cooling baseline for a MC

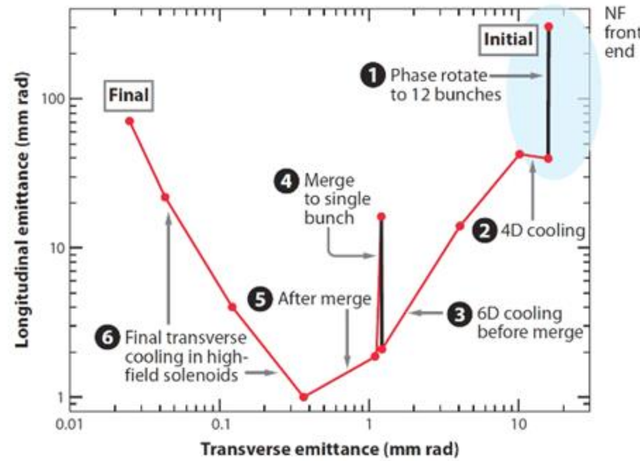


Complete cooling channel simulation



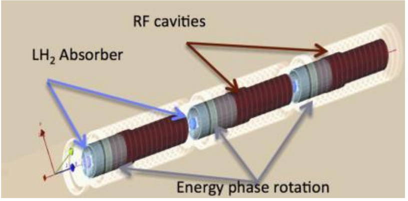
- 6D emittance reduction by 5 orders of magnitude (point 2 to 5). Distance ~ 900 m

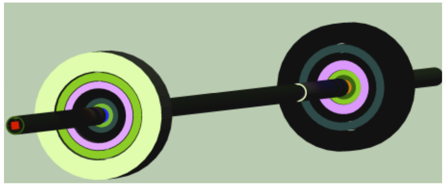




Parameters end of cooling channel	MAP Goal	Channel
Emit., Trans. (mm)	0.30	0.28
Emit., Long. (mm)	1.50	1.57
Particles #	4.7×10^{12}	5.9×10^{12}

- Final cooling design with ~30 T solenoids (point 5 to 6)





Note: A complete cooling scheme with gas filled RF has been also achieved (not shown)

International MICE at RAL

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Demonstration of cooling by the Muon Ionization Cooling Experiment

The MICE collaboration

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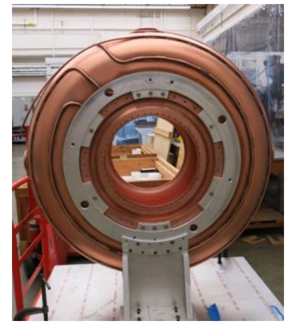
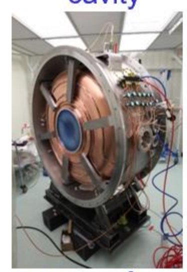


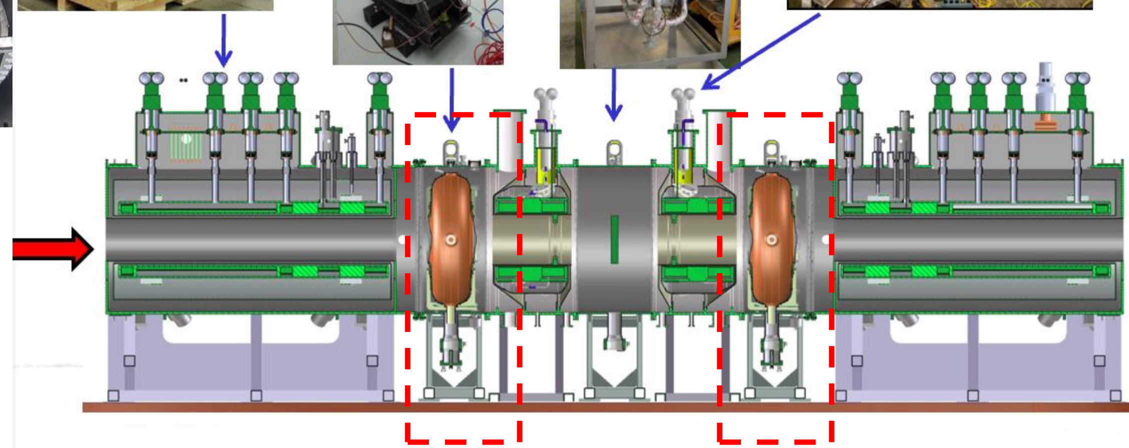
solenoid

cavity



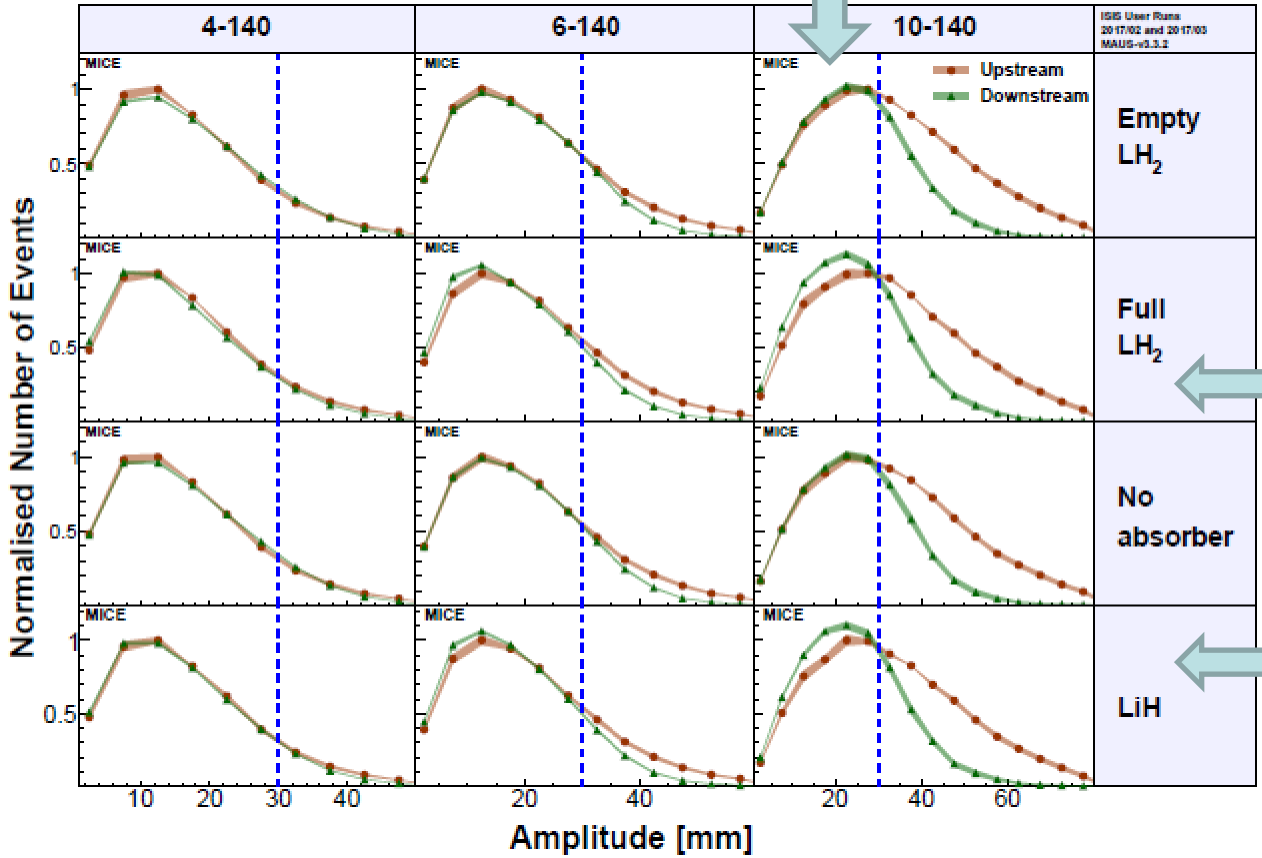
absorber

focus coil



Demonstration of transverse ionization cooling

Beam within acceptance

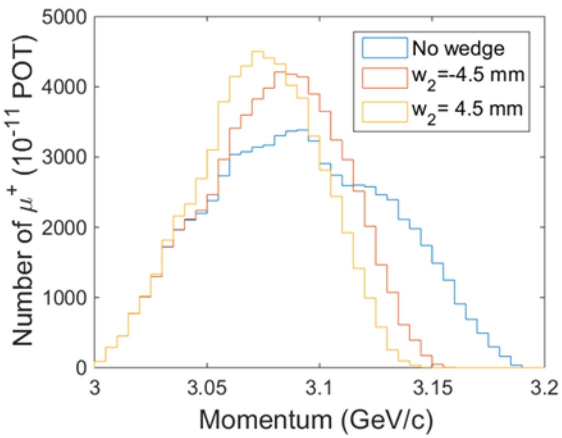


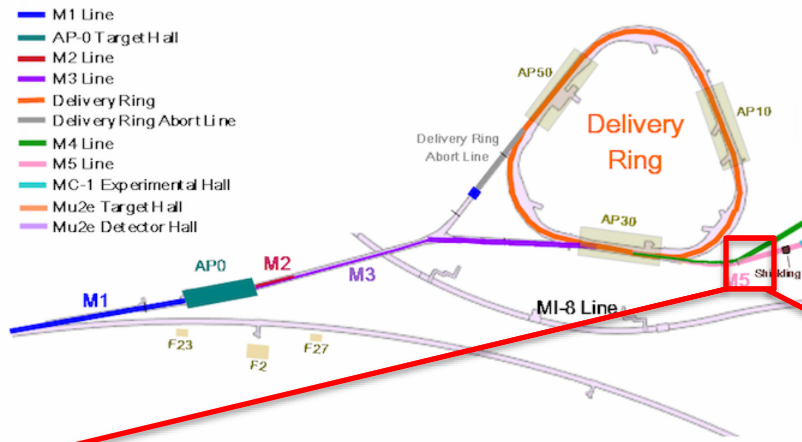
Cooling

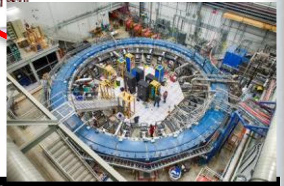
Cooling

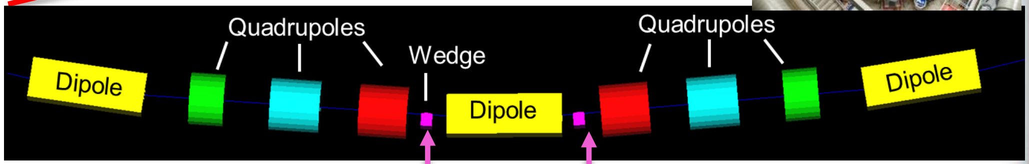
Demonstration of emittance exchange at the Fermilab Muon Campus

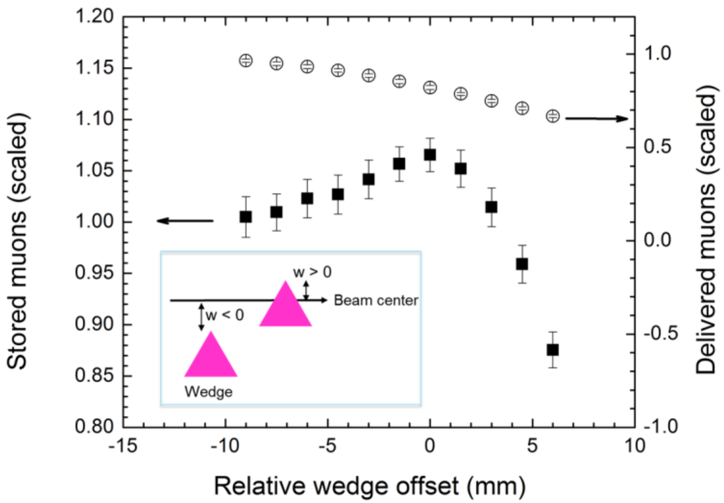
- Proof-of-principle experiment: Demonstrated 8% gain

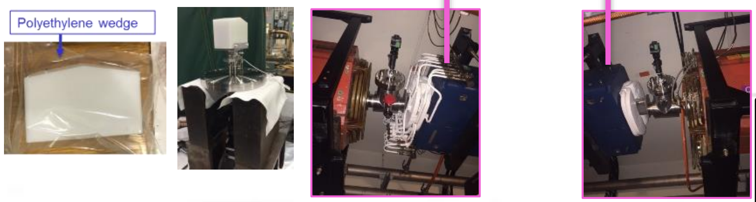


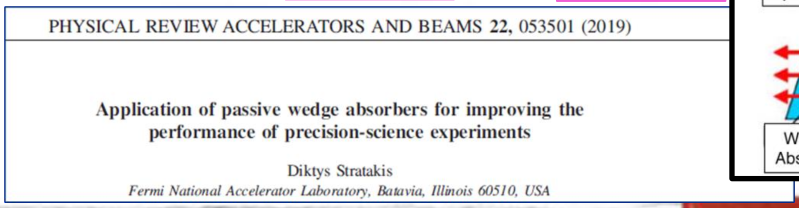












PHYSICAL REVIEW ACCELERATORS AND BEAMS 22, 053501 (2019)

Application of passive wedge absorbers for improving the performance of precision-science experiments

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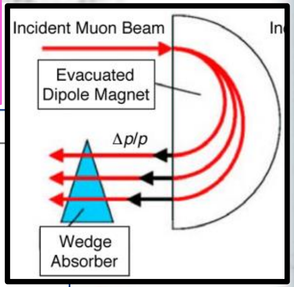
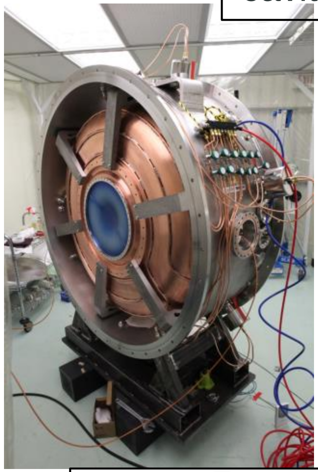
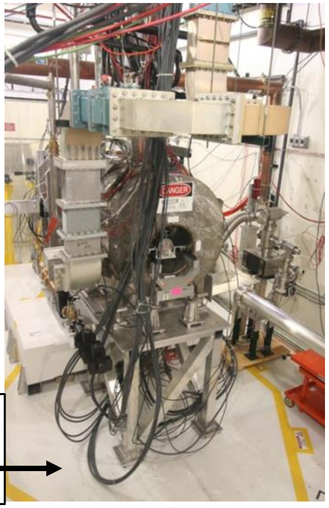


RF normal conducting cavity R&D

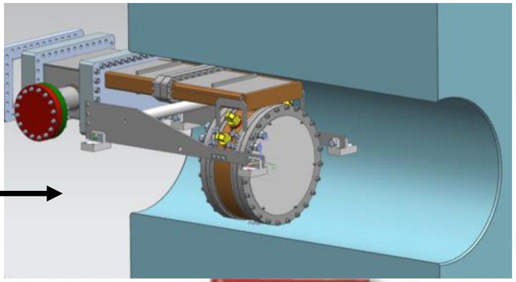
- Fermilab Muon Test Area (MTA): A dedicated facility to study limitations of NC RF with and without B-fields
- Experimental R&D conducted at 805 MHz for vacuum and high pressure cavities, and at 201 MHz for a MICE prototype cavity
- Key findings:
- Modular vacuum RF cavity reached 50 MV/m in 3 T field
- Gas-filled RF cavity reached 60 MV/m without B dependence
- MICE cavity with Be windows and module with vacuum protection reached to the design goals

201 MHz MICE cavity prototype





805 MHz cavity in 3T test



805 MHz with removable plates

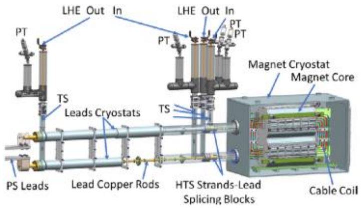
Magnet technology (I)

A multi-TeV muon collider demands significant advances in superconducting magnet technology including those offered by the HTS.

- Large aperture, high-field arc dipoles (14 cm bore, 20 T, 6 TeV MC)
  - Capable of handling large heat load and large magnet stress
- Large aperture, high-field IR quads (15 cm bore, 15 T peak field, 6 TeV MC)
  - Driven by large beta values and magnet protection from muon decay products.
- Achieving both of above requires to drive Nb_3Sn technology to limit
- High field solenoid (>30 T) for muon cooling
  - Where HTS is an enabling technology.
- HTS is possibly useful for fast cycling magnets needed for acceleration
- HTS has seen huge advances in recent years:
  - Especially with solenoids. Examples include 32 T all superconducting user solenoid, 28 T commercial NMR magnet, 45.5 T record DC magnetic field.
  - Accelerator dipole technologies being pursued at CERN, US MAP with several unique and new concepts. US MDP develops high current density Bi-2212 round wire and stress management canted cosine theta (CCT) magnets

Magnet technology (II)

HTS rapid cycling magnets



Nuclear Inst. and Methods in Physics Research, A 943 (2019) 162490

Contents lists available at ScienceDirect

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journal homepage: www.elsevier.com/locate/nima

Record fast-cycling accelerator magnet based on HTS conductor

Henryk Piekarz *, Steven Hays, Jamie Blowers, Brad Claypool, Vladimir Shiltsev

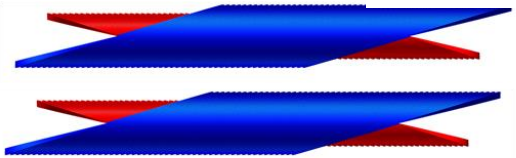
Fermi National Accelerator Laboratory, Batavia, IL 60510, USA

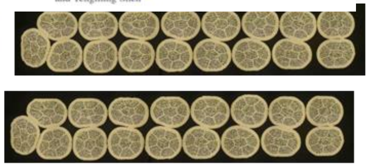
New HTS magnet tech – Bi-2212 CCT

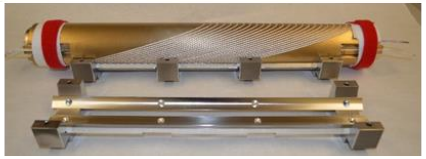
IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 28, NO. 4, JUNE 2018

Designs and Prospects of Bi-2212 Canted-Cosine-Theta Magnets to Increase the Magnetic Field of Accelerator Dipoles Beyond 15 T

Laura Garcia Fajardo, Lucas Brouwer, Shlomo Caspi, Stephen Gourlay, Soren Prestemon, and Tengming Shen







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New HTS magnet tech – REBCO CORC CCT

Article

Dipole Magnets above 20 Tesla: Research Needs for a Path via High-Temperature Superconducting REBCO Conductors

Xiaorong Wang *, Stephen A. Gourlay and Soren O. Prestemon

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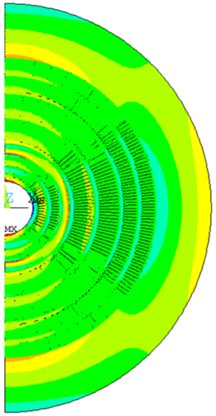
Hybrid Nb3Sn / HTS magnet



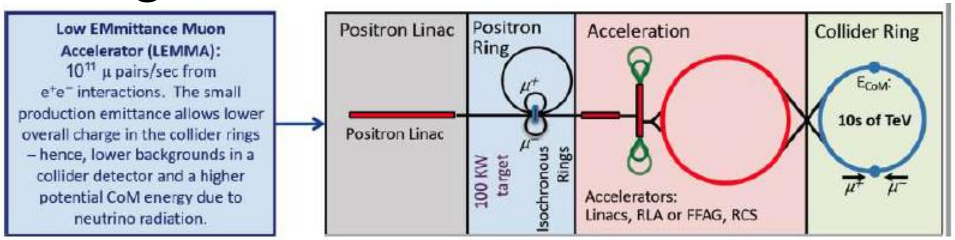
U.S. MAGNET DEVELOPMENT PROGRAM

A 13 T, 50 mm bore Nb_3Sn (CCT6) /HTS hybrid dipole magnet in design at LBNL for US MDP

Special thanks to Tengming Shen for this slide!

Areas of further research

- Magnet technology: High field, multi-Tesla SC magnets for muon production, cooling, acceleration and collision.
- RF technology: High gradient, robust normal conducting rf cavities for cooling and power-efficient superconducting rf for acceleration.
- Lattice designs: Shorter cooling channel designs, end-to-end lattice designs for acceleration towards TeV-scale energies, collider ring lattice designs for > 3 TeV CoM
- Detector technology: Concepts that can sustain muon decay background for multi-Tev energies
- Alternative concepts:
  - 45 GeV $e^+e^- \rightarrow$ muons



Comments

- Increasingly growing interest in muon collider from particle physics community, especially in Europe;
- Joining the international muon collider collaboration efforts under discussions
  - As individual institute or coordinated US efforts?
  - Leveraging and resuming previous US MAP R&D?
- A breakthrough towards a proton driven MC through MICE:
  - A successful muon cooling demonstration, but took nearly two decades;
  - Future R&D should take advantages of existing infra-structures and resources of collaboration institutes.
- AF should be more actively involved in the upcoming Snowmass process with the particle physics community to define the needed muon collider R&D.
  - Physics case first approach and augment it with the accelerator effort